The cosmic-ray puzzle and the census of the interstellar medium: the *Fermi* LAT view of Cassiopeia, Cepheus and the Perseus arm.

L. Tibaldo[1,2] and I. A. Grenier[2]
on behalf of the *Fermi* LAT collaboration
[1] *INFN – Sezione Di Padova & Dipartimento di Fisica "G. Galilei" – Università di Padova, I-35131 Padova, Italy*
[2] *Laboratoire AIM, CEA-IRFU/CNRS/Université Paris Diderot, Service d'Astrophysique, CEA Saclay, 91191 Gif sur Yvette, France*

Diffuse γ-ray emission arising from interactions of cosmic rays with the interstellar gas traces the densities of both of them throughout the Milky Way. We discuss the results obtained from the analysis of *Fermi* LAT observations in the region of Cassiopeia and Cepheus, towards the Perseus spiral arm. We find that the γ-ray emissivity of local gas is consistent with expectations based on the cosmic-ray spectra measured at the Earth. The emissivity decreases from the Gould Belt to the Perseus arm, but the measured gradient is flatter than predictions by a propagation model based on a cosmic-ray source distribution peaking in the inner Galaxy as suggested by pulsars. The $X_{\rm CO} = N({\rm H_2})/W_{\rm CO}$ conversion factor moderately increases by a factor ~ 2 from the Gould Belt to the Perseus arm. The presence of additional gas not properly traced by H I and CO surveys in the Gould Belt is suggested by the correlation between γ-rays and thermal emission from cold interstellar dust.

1. INTRODUCTION

More than a century after the discovery of cosmic rays (CRs), their origin is still mysterious and their propagation in the interstellar space subject of long-standing debates. Interactions between CRs and interstellar gas give rise to γ rays through π^0 decay and Bremsstrahlung radiation. In addition, CR electrons and positrons produce γ rays through inverse Compton scattering on the low energy interstellar radiation field. Thus, γ rays can probe CR densities in the solar neighborhood, beyond the direct measurements in the solar system, as well as in remote parts of the Galaxy.

On the other hand, the interstellar γ-ray emission usefully complements gas and dust tracers at other wavelengths to probe the interstellar medium (ISM) column densities. Two main radio/microwave tracers of the ISM have long been used in γ-ray astrophysics: the 21 cm line of atomic hydrogen, H I, and the 2.6 mm line of carbon monoxide, CO. There are, however, open issues in the derivation of gas column densities from these observations, and hints that their combination does not provide an exhaustive census of the gas in the ISM.

In this contribution, we add a few pieces to this intriguing puzzle with the use of *Fermi* Large Area Telescope (LAT) data for the second Galactic quadrant, at $100° \le l \le 145°$, $-15° \le b \le 30°$. This region has been selected due to the presence of conspicuous atomic and molecular complexes and the good kinematic separation between the different structures seen along the line of sight. Moving toward the outer Galaxy, the region encompasses complexes that are part of the Gould Belt (within ~ 300 pc from the Solar System), of the local arm (~ 1 kpc), of the Perseus arm ($2.5-4$ kpc) and of the outer spiral arm (> 5 kpc). The analysis is described in detail in [1]. We summarize below the main results and discuss their physical implications.

2. GAMMA-RAY EMISSION FROM THE LOCAL INTERSTELLAR MEDIUM

The γ-ray emissivity of atomic gas can be estimated by comparing γ-ray and radio data because the 21 cm line of the H I hyperfine transition allows us to derive hydrogen column densities, N(H I). The results presented here are based on the often-used assumption (in γ-ray astrophysics) of a uniform H I spin temperature of 125 K. There are, however, large uncertainties in the gas spin temperature, as well as non-uniformities within a single interstellar complex. The issue of the N(H I) determination will be further discussed in Section 5.

In Fig. 1 we show the differential emissivity per H I atom measured in the Gould Belt. The results are compared with the predictions by GALPROP, a widely used code for CR propagation [2, 3]. The results are consistent with an independent study of LAT measurements at intermediate Galactic latitudes in the third quadrant [4]. The H I emissivity in the Gould Belt obviously exceeds the GALPROP prediction by $\sim 50\%$.

However, the normalization of the spectrum is consistent with the expectations within the actual constraints. In the energy range considered (200 MeV – 10 GeV) the emission is dominated by the pionic component due to hadronic interactions. An important source of uncertainty comes from systematic errors in CR measurements: the current literature reports differences up to $\sim 20\%$ for the proton spectrum. An

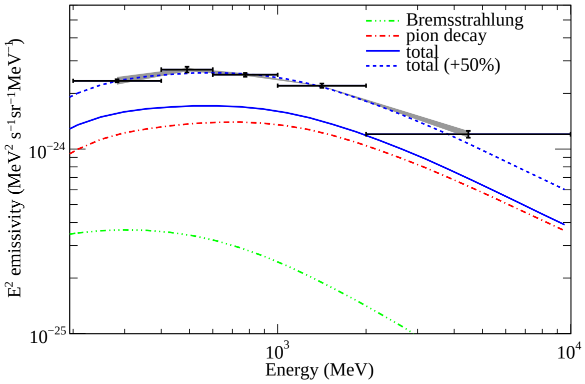

Figure 1: Differential emissivity per H I atom measured in the Gould Belt. Black points are our measurements, the shaded area gives the systematic uncertainties due to the LAT event selection efficiency. The lines represent the predictions by the GALPROP model `54_71Xvarh7S`.

additional $\sim 30\%$ uncertainty is due to the contribution from heavier nuclei in both CRs and the ISM. The GALPROP model we adopted, following the method by Dermer [5, 6], predicts an effective enhancement of ~ 1.45 with respect to pure *p*-*p* emissivities. Different authors, however, report values as high as $1.75-2$ [7][1].

Provided a 50% scaling of the emissivity, the spectral shape is in good agreement with the expectations. Thus we can conclude that CR nuclei in the local ISM are similar to those measured at Earth: further constraints will be given by improved direct measurements of CRs (by missions like PAMELA and AMS02).

This is an additional evidence that LAT measurements are not consistent with the GeV excess seen by EGRET [see e.g. 8, 9], as already deduced by LAT observations at intermediate Galactic latitudes [10]. A deviation with respect to the expected spectral shape of diffuse γ-ray emission was observed by EGRET over the whole sky for energies $\gtrsim 1$ GeV, leading to several possible interpretations: instrumental effects, differences between typical CR spectra in the ISM and those in the proximities of the Earth, dark matter annihilation. The GeV excess was noticed also in the H I emissivity of local interstellar complexes [11], being inconsistent with the results of our analysis. The same kind of difference is noticed in the spectra of bright point sources, notably for the Vela pulsar [12], and so the differences between the spectra measured by EGRET and those measured by the LAT are plausibly instrumental in origin.

[1]The origin of the discrepancies is still unclear, either due to the calculation method (e.g. parametrization of the reaction yields versus numerical simulations) and/or to differences in the CR spectra within the experimental constraints.

3. THE X_{CO} GRADIENT IN THE OUTER GALAXY

The molecular phase of the ISM is difficult to trace, because its major constituent, H_2, does not have observable emission lines in its cold phase. The 2.6 mm line of the CO $J = 1 \to 0$ transition has often been used as a surrogate tracer of molecular masses. Observations, notably virial mass calculations, suggest that the velocity-integrated antenna temperature W_{CO}, despite the optical thickness, is proportional to the total mass in the emitting region [13].

The conversion factor which transforms W_{CO} intensity into $N(H_2)$ column density is known as $X_{CO} = N(H_2)/W_{CO}$. For many years it has been considered as uniform across the Galaxy, but we have now evidence from virial masses [14], from COBE/DIRBE observations [15], and from the X_{CO} dependence on metallicity in external galaxies [16] that it increases with Galactocentric radius. Such an increase was shown to be consistent with EGRET data [17], but the limited performance of previous γ-ray telescopes did not allow to get accurate measurements in the outer Galaxy [11, 18].

High-energy γ-ray observations provide important constraints on X_{CO} values. Since the molecular binding energy is negligible with respect to the energy scale of the γ radiation processes, the emissivity per H_2 molecule is twice the emissivity per H I atom for gas threaded by the same CR flux. This statement relies on the assumption that CR diffusion lengths are large enough to ensure similar CR spectra in the atomic and molecular phases of a complex (i.e. they do not vary significantly over distances of tens of pc) and that CRs penetrate molecular clouds uniformly to their core in spite of the enhanced magnetic fields (idea still under debate).

The results of our work allowed us to correlate the integrated emissivity per W_{CO} unit (q_{CO}) and per H I atom ($q_{\rm H\,I}$) in different regions along the line of sight, for several energy bands from 200 MeV to 10 GeV. The results are shown for the local arm in Fig. 2.

The good linear correlation supports the assumption of similar spectra in the atomic and molecular phases of the clouds and the energy-independent penetration of CRs to the molecular cores. The slope of the linear relation provides an estimate of the X_{CO} ratio. Good linear correlations are also found for the Gould Belt clouds and in the Perseus arm. The values of X_{CO} in the different regions are summarized in Fig. 3 as a function of Galactocentric radius.

The results confirm a significant but moderate increase of X_{CO} with Galactocentric radius. The gradient is consistent with the metallicity decrease in the outer Milky Way and the strong relation seen between metallicity and X_{CO} in external galaxies [16]. This relation is plausibly due to poor self-shielding against

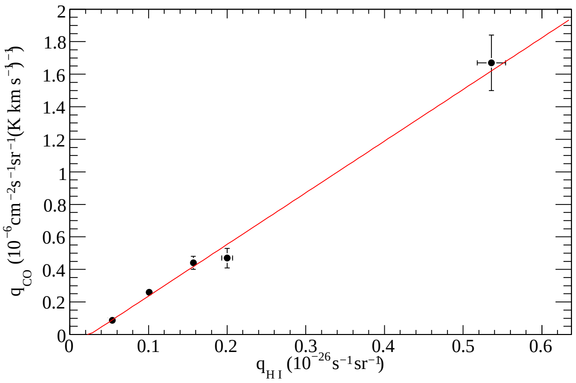

Figure 2: Correlation between $q_{\rm CO}$ and $q_{\rm H\,I}$ over 5 energy ranges between 200 MeV and 10 GeV in the local arm clouds. The solid red line represents the best linear fit. The fit uses the measurement uncertainties on both axes.

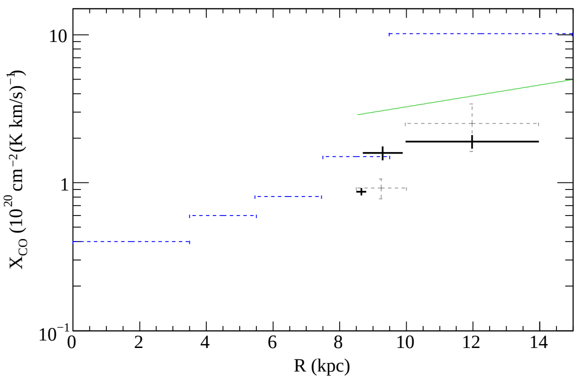

Figure 3: Black points: $X_{\rm CO}$ values measured in the Gould belt, local and Perseus arm (from left to right). Blue dashed line: model by Strong et al. [17]. Green solid line: the conversion function based on virial masses by Nakanishi and Sofue [19].

CO photodissociation by UV radiation in low metallicity environments.

Our results do not support the extremely large gradient proposed by Strong et al. [17] beyond the solar circle (dashed blue line in Fig. 3). The latter was introduced on the basis of non-γ-ray data to alleviate the *CR gradient problem* (see below Section 4). We find a value significantly lower than the prediction of this model for the molecular complex associated with NGC 7538 and Cas A in the Perseus arm, which is the most massive molecular complex beyond the solar circle.

The values of $X_{\rm CO}$ we measured are systematically lower than the conversion law derived by Nakanishi and Sofue [19] from virial masses. We have verified that a difference of comparable magnitude is found for our clouds between the masses derived from the $X_{\rm CO}$ ratios just measured and the virial masses (based on the same CO data used for the γ-ray analysis) [1]. An instrumental origin of the discrepancy (e.g. calibration differences between different CO datasets) is therefore unlikely. As already said, the γ-ray masses may be biased by the non-uniform penetration of CRs within the dense cores of the clouds. The limited spatial resolution of the γ-ray data may also lead to separation problems between the molecular phase of a cloud and its dense atomic envelope. On the other hand, virial masses rely on rather crude hypotheses: spherical clouds with simple density profiles and turbulent support to hold a cloud in equilibrium against gravitational collapse. The effects of magnetic support are rarely considered (they were not in our calculation) and intrinsic velocity gradients can broaden the velocity dispersion. The virial estimate also corresponds to the total dynamical mass, whereas the γ-ray estimate corresponds to the mass spatially associated with CO. Gas not properly accounted for by $W_{\rm CO}$ intensities could explain, at least in part, the differences between the virial and γ-ray masses (see below Section 5).

4. THE COSMIC-RAY DENSITY GRADIENT IN THE OUTER GALAXY

The CR origin is still unclear. The EGRET non-detection of the Small Magellanic Cloud [20], an external galaxy member of the local group, highlighted that its CR content significantly differs from that of the Milky Way. The EGRET upper limit was recognized as evidence that CRs, at least below $\sim 10^{15}$ eV, have a Galactic origin. Supernova remnants (SNRs) have been considered for many years the best candidates as CR accelerators in our Galaxy. Whereas diffusive acceleration of electrons by SNR shock waves is obvious from multiwavelength observations, only recently we started accumulating indirect evidence for the acceleration of CR nuclei γ-ray observations in the TeV [21–23] and GeV domain [24].

On the other hand, the distribution of SNRs in the Galaxy is very poorly determined [25] because of the sparsity of the known sample (a few tens) and its large selection effects. Since the COS-B era it is well known that the gas γ-ray emissivity gradient across the outer Galaxy is much flatter than expected from the decline in SNR detections [26].

Strong et al. [17] proposed to use the observed pulsar distribution to trace CR sources because of their richer sample [27]. Large uncertainties in the distance derivation from the dispersion measurements can, however, easily bias their radial distribution. The decline in pulsar counts in the outer Galaxy is even steeper than the SNR one, strengthening the *CR gradient problem.* Strong et al. [17] attempted to alleviate this problem by increasing the amount of molecular gas in the outer Galaxy, invoking a strong increase of

$X_{\rm CO}$ beyond the solar circle. Yet, tuning the $X_{\rm CO}$ ratio does not explain the flat $q_{\rm H\,I}$ emissivity gradient recorded in the ubiquitous and massive atomic phase [26, 28]. As discussed in Section 3 this solution is disfavored by LAT measurements.

Our measurements of the H I emissivity across the outer Galaxy are shown in Fig. 4.

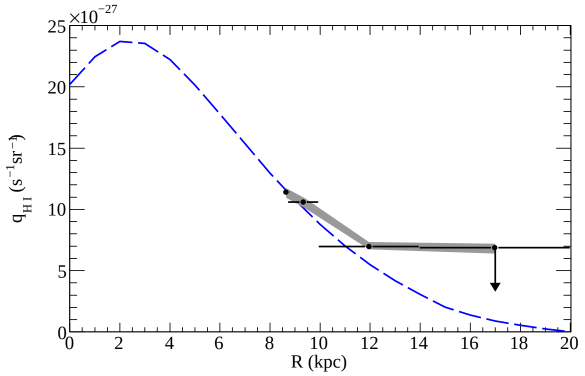

Figure 4: H I emissivities integrated between 200 MeV and 10 GeV ($q_{\rm H\,I}$) measured in the Gould belt, local, Perseus and outer arm (from left to right). Black points are our measurements, the grey shaded area represents the systematic uncertainties in the LAT event selection efficiency. The blue dashed line gives the prediction by the GALPROP model `54_71Xvarh7S`.

The results are compared with the predictions by a GALPROP model which uses a CR source distribution derived from pulsars. The *CR gradient problem* is confirmed by LAT data: the measured decline in emissivity is much flatter than the prediction by GALPROP for the pulsar (Fig. 4) and also the SNR distribution (*Fermi* LAT collaboration, in preparation).

Systematically underestimating the remote N(H I) densities as the result of self-absorption phenomena can lead to a bias in the emissivity gradient. Correcting for H I self absorption, Gibson et al. [29] suggested that a significant amount of H I mass has been overlooked by emission surveys in the second quadrant for the outer Galaxy. The large emissivity in the outer Galaxy may be explained also by a population of unresolved sources clustering in the Perseus arm structures.

On the other hand, if the flat gradient is real, it challenges either the SNRs as CR parent population or the modeling of CR diffusion across the Galaxy. A possible explanation is provided by the large uncertainties on the SNR distribution. Additionally, the CR propagation parameters are usually derived from the isotopic composition of CRs measured at Earth [see e.g. 2], a reasonable assumption, but not required by observational constraints. An alternative scenario is given by non-uniform CR diffusion [30].

5. THE TRACERS OF THE INTERSTELLAR MEDIUM IN THE GOULD BELT

The modeling of the γ-ray interstellar emission based on the combination of H I and CO data is being challenged by observations. EGRET data, compared with other tracers, already suggested that a significant amount of gas is not properly traced by these radio/microwave lines [31]. The nearby, off-plane, clouds located in the Gould Belt are well suited to probe ISM tracers, both because there is little confusion along the line of sight and because the higher linear resolution of the γ-ray data within the clouds allows a good separation of the emission arising from the different phases and sources.

Following the method proposed by Grenier et al. [31], we have used interstellar dust as an additional gas tracer under the assumption that dust grains are well mixed with gas in the cold and warm phases of the ISM under study. We have used the total dust column densities provided by the color excess E(B − V) map by Schlegel et al. [32]. From this map we have subtracted the parts linearly correlated with the best-fit combination of N(H I) and $W_{\rm CO}$ maps built for the four regions separated along the lines of sight, from the Gould Belt to the outer arm [1].

The residual map is shown in Fig. 5 on the left. Within a few degrees from the Galactic plane, the map exhibits clumps of positive and negative residuals. Their origin is unclear because of the intrinsic limitations of the E(B − V) map near the plane [32]. At intermediate latitudes ($|b| > 5°$), the map is dominated by structured envelopes of positive residuals surrounding the Gould Belt CO clouds. For comparison the $W_{\rm CO}$ map is shown on the right of Fig. 5. Smaller negative residuals are found toward the dense CO cores.

Adding the E(B − V) residual map significantly improves the fit to the γ-ray data [1]. Given the spatial correlation, we compared the γ-ray emissivities per unit of E(B − V) residuals ($q_{\rm EBV}$) with the emissivities per H I atom ($q_{\rm H\,I}$) in the Gould-Belt clouds. The results are shown in Fig. 6.

The good linear correlation between $q_{\rm EBV}$ and $q_{\rm H\,I}$ over 2 decades in energy suggests that the same process produces the γ rays associated with H I and the dust-traced component.

The γ-ray emission arising from hadronic interactions of CRs with dust grains is too faint to be detected. The IC emission coming from dust infrared emission up scattered by CR electrons is also expected to be faint and spectrally different from the π^0-decay radiation associated with H I [31]. Therefore, the results point to the presence of additional gas which is not properly accounted for in the N(H I) and $W_{\rm CO}$ maps. The negative residuals seen towards the CO

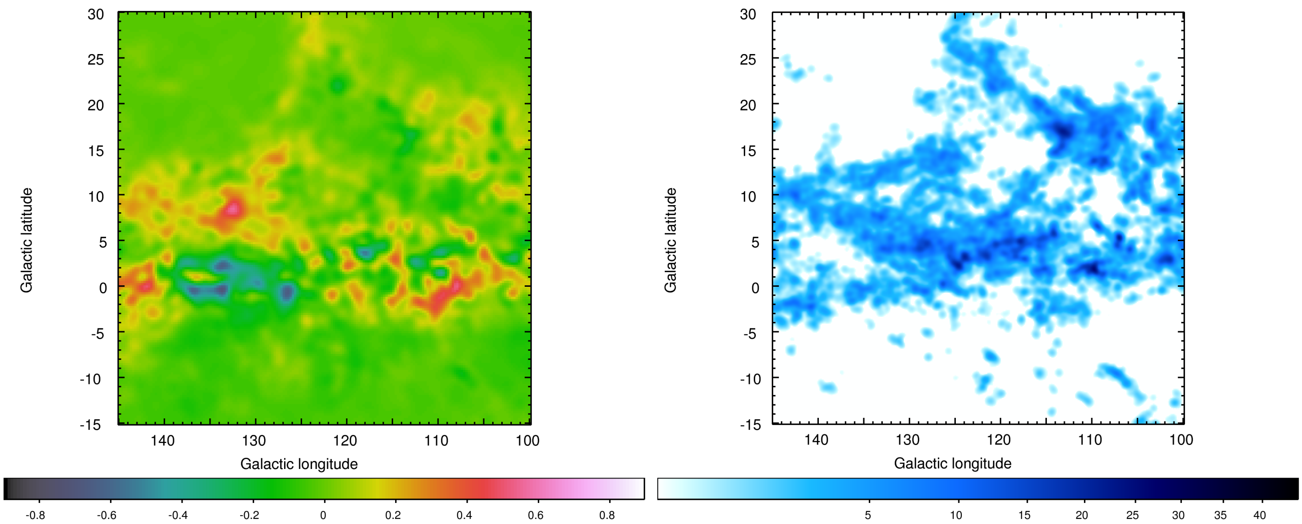

Figure 5: Maps of the region of Cassiopeia and Cepheus. Left: E(B − V) residuals (magnitudes), obtained from the map by Schlegel et al. [32] after the subtraction of the parts correlated with $N(\mathrm{H\,I})$ and W_{CO} maps [1]. Right: W_{CO} (K km s^{-1}) in the Gould Belt region, from the 2.6 mm survey of the CfA telescope [33].

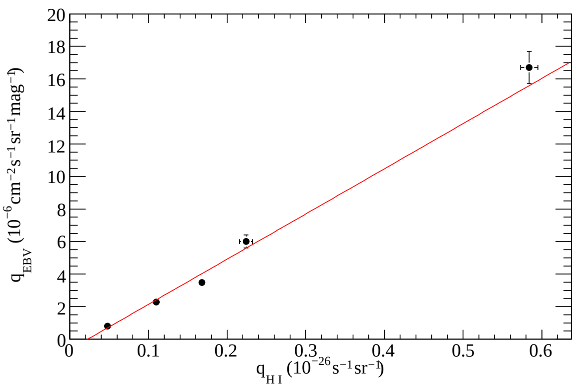

Figure 6: Correlation between q_{EBV} and $q_{\mathrm{H\,I}}$ in the Gould Belt over 5 energy ranges between 200 MeV and 10 GeV. The solid red line represents the best linear fit.

cores can be interpreted as small local variations in the dust-to-gas ratio or in the dust thermal emissivity in the denser, well-shielded parts of the molecular clouds. The nature of the additional gas, however, is not determined yet.

Substantial uncertainties result from the approximations applied to handle the radiative transport of the H I lines. The choice of a uniform spin temperature, T_S = 125 K, has often been adopted in the past, as in our study. Recent absorption surveys [34] propose higher values in the outer Galaxy (250 − 400 K) which would yield $N(\mathrm{H\,I})$ densities lower than the present estimates. Conversely, colder and denser H I gas with T_S as low as 30 − 40 K is quite abundant in the mid-latitude clouds [35]. This phase contributes much larger $N(\mathrm{H\,I})$ column-densities than the estimates based on a uniform spin temperature of a few hundreds K. Self absorption could also bias the $N(\mathrm{H\,I})$ column densities to low values.

On the other hand, at the interface between the atomic and CO-traced phase of an interstellar complex we might find an additional phase where H_2 exists but it is not well mixed with CO (e.g. because H_2 is more efficiently self-shielded than CO in the low extinction range) or densities are too low to excite the CO 2.6 mm line transition [36]. A poor correlation with W_{CO} maps and, conversely, a good correlation with the E(B − V) color excess has already been shown for alternative molecular tracers (like the 9 cm line of CH) in translucent molecular clouds, and possibly proposed for the translucent envelopes of giant molecular clouds [37].

Acknowledgments

The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES

in France for science analysis during the operations phase is also gratefully acknowledged.

LT is partially supported by the International Doctorate on AstroParticle Physics (IDAPP) program.

References

1 A. A. Abdo et al., Astrophys. J. **710**, 133 (2010), arXiv:0912.3618.
2 A. W. Strong and I. V. Moskalenko, Astrophys. J. **509**, 212 (1998), arXiv:astro-ph/9807150.
3 A. W. Strong, I. V. Moskalenko, and V. S. Ptuskin, Annual Review of Nuclear and Particle Science **57**, 285 (2007), arXiv:astro-ph/0701517.
4 A. A. Abdo et al., Astrophys. J. **703**, 1249 (2009), arXiv:0908.1171.
5 C. D. Dermer, Astrophys. J. **307**, 47 (1986).
6 C. D. Dermer, Astron. & Astrophys. **157**, 223 (1986).
7 M. Mori, Astroparticle Phys. **31**, 341 (2009), arXiv:0903.3260.
8 S. D. Hunter et al., Astrophys. J. **481**, 205 (1997).
9 A. W. Strong, I. V. Moskalenko, and O. Reimer, Astrophys. J. **613**, 962 (2004), arXiv:astro-ph/0406254.
10 A. A. Abdo et al., Phys. Rev. Lett. **103**, 25, 251101 (2009), arXiv:0912.0973.
11 S. W. Digel et al., Astrophys. J. **555**, 12 (2001).
12 A. A. Abdo et al., Astrophys. J. **696**, 1084 (2009), arXiv:0812.2960.
13 P. M. Solomon and J. W. Barrett, in *Dynamics of Galaxies and Their Molecular Cloud Distributions*, edited by F. Combes & F. Casoli, vol. 146 of *IAU Symposium*, p. 235 (1991).
14 S. Digel, P. Thaddeus, and J. Bally, Astrophys. J. Lett. **357**, L29 (1990).
15 T. J. Sodroski et al., Astrophys. J. **452**, 262 (1995).
16 F. P. Israel, Astron. & Astrophys. **328**, 471 (1997), arXiv:astro-ph/9709194.
17 A. W. Strong et al., Astron. & Astrophys. **422**, L47 (2004), arXiv:astro-ph/0405275.
18 S. W. Digel et al., Astrophys. J. **463**, 609 (1996).
19 H. Nakanishi and Y. Sofue, Publ. Astron. Soc. Jpn. **58**, 847 (2006), arXiv:astro-ph/061076.
20 Y. C. Lin et al., Astrophys. J. Suppl. **105**, 331 (1996).
21 J. Albert et al., Astrophys. J. Lett. **664**, L87 (2007), arXiv:0705.3119.
22 F. Aharonian et al., Astron. & Astrophys. **481**, 401 (2008), arXiv:0801.3555.
23 V. A. Acciari et al., Astrophys. J. Lett. **698**, L133 (2009), arXiv:0905.3291.
24 A. A. Abdo et al., Astrophys. J. Lett. **706**, L1 (2009).
25 G. L. Case and D. Bhattacharya, Astrophys. J. **504**, 761 (1998), arXiv:astro-ph/9807162.
26 A. W. Strong et al., Astron. & Astrophys. **207**, 1 (1988).
27 D. R. Lorimer, in *35th COSPAR Scientific Assembly*, vol. 35 of *COSPAR, Plenary Meeting*, p. 1321 (2004).
28 A. W. Strong and J. R. Mattox, Astron. & Astrophys. **308**, L21 (1996).
29 S. J. Gibson et al., Astrophys. J. **626**, 195 (2005), arXiv:astro-ph/0503117.
30 C. Evoli et al., Journal of Cosmology and Astro-Particle Physics **10**, 18 (2008), arXiv:0807.4730.
31 I. A. Grenier, J.-M. Casandjian, and R. Terrier, Science **307**, 1292 (2005).
32 D. J. Schlegel, D. P. Finkbeiner, and M. Davis, Astrophys. J. **500**, 525 (1998), arXiv:astro-ph/9710327.
33 T. M. Dame, D. Hartmann, and P. Thaddeus, Astrophys. J. **547**, 792 (2001), arXiv:astro-ph/0009217.
34 J. M. Dickey et al., Astrophys. J. **693**, 1250 (2009), arXiv:0901.0968.
35 C. Heiles and T. H. Troland, Astrophys. J. **586**, 1067 (2003), arXiv:astro-ph/0207105.
36 M. Lombardi, J. Alves, and C. J. Lada, Astron. & Astrophys. **454**, 781 (2006), arXiv:astro-ph/0606670.
37 L. Magnani et al., Astrophys. J. **586**, 1111 (2003).